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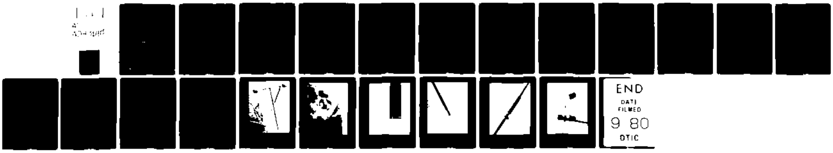

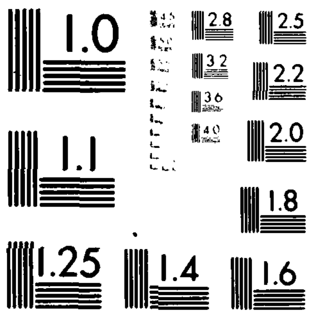

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(6) BALLOON-SUPPORTED ANTENNA FOR LORAN C/D NAVIGATION SYSTEM

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Analysis of corona losses on a proposed balloon-supported Loran antenna indicated the planned design could not be operated at full voltage because losses would far exceed the available power. This study, and a comparison study of expected corona loss on the operational antenna, pointed the way to a successful design. Special top-loader-tethers were procured, and essential hardware was built to implement the design. Electrical constants were measured in a launch test, after which interface hardware was produced for an operational test that was carried out at Anniston, Alabama.

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ILLUSTRATIONS

BALLOON-SUPPORTED ANTENNA FOR LORAN C/D NAVIGATION SYSTEM

1. INTRODUCTION

When this contract began plans were already under way to build and test a balloon-supported antenna that could serve as an emergency back-up for the tower structures normally used in the Loran C/D navigation system. An electrical design had been specified by the Rome Air Development Center, Deputy for Electronic Technology, Hanscom AFB, which was expected to exhibit electrical constants sufficiently close to those of the tower to allow it to be tuned using the transmitter's antenna-matching unit. It consisted of a vertical element 500 feet long, and three symmetrically spaced top loaders of 700-foot length, each making an angle of about 49° with the vertical. Also, six radial elements of 300-foot length were to be laid on the ground, with connections to the earth at the central junction and at the outer ends of the radial elements. Standard aluminum cable of 1/0 size was specified for the vertical element, but the top loaders and the radials on the ground were to be solid aluminum of 3/16-inch diameter.

2. PLANNED IMPLEMENTATION OF ORIGINAL DESIGN

Responsibility for implementing the design and for erecting it on a tethered balloon belonged to the Aerospace Instrumentation Division at AFGL. Initial planning accepted the notion that the electrical design was adequate, and that the problem was to erect the specified structure using correct geometry and dimensions. On this basis it appeared appropriate to simply attach the antenna elements to a tripod-tether arrangement made of insulating KEVLAR cables. A plan which met the geometrical requirements had three tether cables arranged as a tripod, each leg being 788 feet long, and anchored at 120° intervals around a circle of 596-foot radius, with a single tether cable extending up an additional 500 feet from the junction point to the balloon. Top loaders for the proposed antenna were to be banded to the legs of the tripod, and the vertical element was to hang down from the apex point. Antenna elements were to be electrically connected at the apex, and tethers were to be joined there too, all being attached to an aluminum disc 1 1/2 inches thick and 12 inches in diameter. Normal bobbing of the lower end of the vertical element was to be accommodated by two insulating tension devices attached at the bottom.

A procedure for erecting the proposed tripod-tether arrangement was worked out and tested at Holloman AFB, but without the antenna elements present. Methods used are well known to those who work with tethered balloons. A significant feature of the plan was that one of the tripod tethers was employed in the launch operation, serving as a let-up cable after the balloon reached 500 feet. During this phase the two slack legs of the tripod tended to wrap themselves around the leg that was under tension. Twisting was restricted by manually pulling on the slack tethers, but the tendency of the junction plate to turn was a troublesome problem which probably would have been worse if the antenna elements had been present. Use of a tripod leg for balloon let-up presents a second launch problem because the process involves having the taut tether pass through a sheave to a tow vehicle, a procedure that would be difficult, or unworkable, with the top loader banded to the tether.

All of the work, and the planning, that has been mentioned was accomplished before the balloon-supported antenna problem was introduced into this contract.

3. IDENTIFICATION OF THE CORONA PROBLEM

Although the Aerospace Instrumentation Division was not responsible for the antenna design, they were responsible for system safety, and this appeared threatened by corona on the top loaders if the Loran transmitter were to be operated at full voltage, 78,000 volts. Corona could degrade or burn the KEVLAR cables to which the top loaders would be attached, and which hold the balloon. If this happened it would be disastrous. Concern for safety was voiced when the contract began, and as a consequence work was started at Tufts to evaluate the expected loss on the proposed configuration.

This effort had barely begun when a problem developed at one of the Loran transmitting sites which had been in operation about a year; one of the twelve top loaders that extend down 400 feet from the top of the tower failed. Design of those top loaders consists of a double layer of aluminum braid applied over an insulating Phillystran cable of 3/8-inch diameter. A protective polyethylene jacket covers the braid. Outer end of the braid is terminated by a short aluminum sleeve 7-inches long and 1 1/2-inches in diameter, and this in turn is fitted with a donut-shaped corona ring of 7-inch diameter and 1-inch cross section. Taken together the two braids are equivalent in size to a #9 conductor.

Examination showed that the Phillystran material had been burned at the point where the braid joins with the sleeve assembly. What evidently happened was that normal flexing of the cable, which also serves as a guy for the tower, caused the aluminum braid to break at the stiff cylindrical sleeve. Continued flexing caused the ends of the broken braid to be bent and pushed slightly away from the sleeve, thereby allowing the lumped capacitance of the sleeve and corona ring to be electrically isolated from the end of the braid. High voltage on the top loader then caused continual sparkover to the isolated hardware, and this progressively burned the insulating cable until it parted. Involvement with studying this incident provided convincing evidence that the suspected threat to safety was very real, and that the corona question had to be correctly evaluated.

4. EVALUATION OF THE CORONA PROBLEM

Corona on high voltage transmission lines has been a much studied problem for a great many years. Losses depend critically on the voltage gradient at the conductor surface, and they vary as well with ambient pressure and temperature, with roughness of the conducting surface, and with atmospheric conditions, particularly rain, snow, sleet, and fog. Losses are also proportional to frequency, a fact that is particularly important in the antenna application where the frequency is 100 kHz, and the available power is limited to 30 kW.

Commonly used relations for transmission lines are not applicable to the peculiar geometrical arrangement presented by the antenna. However, the basic information can be applied if the voltage gradient at all positions along the antenna can be found. A quasi-stationary solution is adequate because the wavelength at the operating frequency, 100 kHz, is 9821 feet, which makes the top loaders 0.07 wavelengths and the vertical element 0.05 wavelengths. Electrostatic methods can therefore be used to find the charge distribution that gives constant potential everywhere along the cylindrical conducting surfaces. Once the charge distribution is known, the gradients, the corona losses, the currents, and the ohmic losses can be found.

The method used to find the correct charge distribution was to first assume a uniform distribution, then calculate the potential at all positions due to the assumed distribution, and from this compute a new distribution to be used in the next calculation, the process being repeated until the potential everywhere was the same. Because the antenna is in the vicinity of the earth, and the radial ground wires laid on the earth's surface, it is necessary to introduce image elements below the ground plane that have the same dimensions and charge distribution as the antenna elements, but with reversed sign. Inclusion of the images means there are eight separate members to be considered, four antenna elements and four images. Each was broken into 200 equal parts, making a 1600-part representation of the system. The task of properly expressing distances between the various antenna segments in analytical form was carried through, and a computer was instructed to repeatedly solve the problem until the calculated potential everywhere was the same. As expected, the charge density is very high at the ends of the top loaders, so the gradients and the corona losses in those regions are correspondingly large. Also incorporated into the computer program were routines for calculating corona loss on each antenna segment, for summing segment losses to obtain the total loss for the system, and for computing currents, ohmic loss in all segments, and total ohmic loss. Having the charge distribution, and the total charge, allowed the effective capacitance of the antenna to be determined.

Results of the study proved beyond question that the originally proposed balloon-supported antenna would be worthless, even if it were safe, because all the available power from the transmitter would go into corona discharges. Depending on the assumed surface roughness, the predicted corona loss, if operated at 78,000 volts, would be 30 to 100 times larger than the available power. It simply wouldn't work.

5. REVISED ANTENNA DESIGN

Results from the corona analysis, and conclusions concerning the top loader that failed, indicated the originally specified design should be discarded. But before deciding on a new arrangement, calculations were made to determine the expected corona loss on the top loaders of the regularly used Loran antenna, and on the balloon-supported configuration if the same type of top loaders were to be used on that system. Predictions indicated that both antennas would have significant corona, several kilowatts for each, but the loss on the balloon-borne version would be larger by a factor of two or three, depending on assumed surface roughness. An implicit assumption in these calculations was uninsulated conductors, which is the only situation where the empirically established corona relationships are valid. However, it is known that insulation such as the polyethylene jacket does impede corona formation, just as the use of corona dope does, even though the quantitative benefits cannot be predicted. Presence of the polyethylene jacket probably accounts for the fact that the Loran antenna has operated successfully in all kinds of weather, presumably with relatively low corona losses, so it was concluded that the same type of design should be successful for the balloon-supported arrangement.

Based on this view, steps were taken to procure new tethers with built-in top loaders similar to those used with the tower. KEVLAR was chosen for the tether material, with the core size, the double braid construction, and the polyethylene jacket being the same as for the tower arrangement. Also, the termination used at the upper end of the top-loader-guy for the tower antenna was adopted without change for the balloon-supported version. It consists of a potted cylinder 7-inches long and 1 1/2-inches in diameter, threaded at the end to accommodate flexible hardware that electrically and mechanically joins the top-loader-tethers at the apex.

Although no lower-end termination similar to the corona ring was specified for the original design, this was an important omission because losses near the end are much higher than elsewhere. For reasonable surface roughness, about 50% of the loss occurs on the outermost 10% of the length, and about 10% of the loss occurs on the outermost 1%, with very high losses at the tip. In fact losses on the outermost 0.1% of the length would be about one hundred times greater than the loss on the same length segment located 10-segment lengths from the end. Analysis showed that a 6-inch diameter sphere would change the situation completely, and eliminate the serious problem at the tip of the conductor. Spherical terminations were therefore adopted for the balloon-supported structure. Their smaller weight, and particularly the absence of potting, which appeared to be the root of the difficulty with the top loader that failed, are desirable features of the design. Also, the hollow spheres can be readily attached when needed, and easily removed for storage and shipment, which is important for the balloon-supported arrangement.

Two important modifications were made to the vertical element; a thin jacket of insulation was applied, and the lower 10 feet was replaced with a long corona-free termination. Because of its proximity to the earth, the lower end being nominally 10 feet above the surface, corona is very heavily concentrated in this region. Study indicated that three-fourths of the loss would occur on the bottom 10% of the vertical element, with about half on the lower 1% of the length. There was also the problem of keeping the lower end sufficiently fixed in position to allow the antenna to be fed at a position 10 feet up from the bottom, as specified in the original design. A convenient solution to both problems was to use a 10-foot long aluminum tube at the bottom end, with a 2 1/2-foot crossarm at the base, each end of the crossarm being terminated by a 6-inch sphere. Tubular gussets were added to make the inverted-T arrangement rigid. Dimensions of the conducting surfaces were large enough to eliminate the corona problem in the lower region where it is most severe, and the mechanical arrangement permitted convenient attachment of the two insulating hold-downs that applied constant tension. Smooth clamping devices were used for joining the inverted-T to the 1/0 aluminum conductor, and for attaching the vertical element at the apex.

The insulating jacket was put on the 1/0 aluminum cable by applying thick-wall shrink tubing over the entire length, a task that was made relatively simple by inflating the 100-foot lengths of tubing with compressed air and sliding them into position along the cable in the manner of an air bearing.

Mechanically joining the tethers at the apex, and electrically connecting the antenna elements there, constitutes more of a problem than was visualized when the procedural test of the tripod-tether system was performed at Holloman. A solution to the combination of problems was had by making a lightweight corona-free tetrahedron that is large enough to eliminate the twisting problem, sufficiently strong to withstand mechanical forces of 6000 pounds with a factor of safety of three, and capable of carrying the antenna currents. Corners of the tetrahedron were smooth machined surfaces, these being mechanically joined by six aluminum rods of 7/8-inch diameter and 24-inch length. Tongues protruding from each of the three lower corners allowed the top-loader-tethers to be attached by means of special universal joints designed to carry the currents and withstand the tether forces. Provision was made at the top corner for attaching the 500-foot tether that extends up to the balloon, and for making a flexible current-carrying connection with the vertical element that hangs down from there. In addition, provision was made for adding an insulating tether which could be used in the let-up process, replacing the tripod leg previously used. This particular feature was necessary because the new tethers cannot be passed through the sheave under tension. Use of the fourth tether greatly simplifies the launch and take-down procedures, and provides a safety line as well. It can be pulled aside and anchored after the system is erect and the tripod tethers are taut.

6. LAUNCH TEST AND MEASUREMENTS AT HOLLOMAN AFB

A test of the revised antenna design was made at Holloman AFB on 23 March 1977. Purposes of the test were to demonstrate the launchability of the new arrangement, and to measure the electrical constants of the antenna, specifically the equivalent lumped inductance and capacitance. The launch involved the elements that have been described, these having been judged suitable for operational use later on. Rigging at the lower end of the vertical element included the inverted-T and the tension devices, but the heavy corona-free hardware that would be needed to connect the antenna to the transmitter was not involved. The exercise proved conclusively that the changed launch procedure can be accomplished in a straightforward manner. As expected, the sizable dimensions of the tetrahedron provided such a substantial lever arm that no twisting difficulty was experienced.

Effective capacitance of the antenna had been calculated during the computer study, but without the inverted-T, or the spheres on the top loaders. When these are included the result is 3900 picofarads, which is about 4 1/2% below the measured value of 4085 picofarads. Closeness of the agreement is surprising because the ground plane provided by the dry desert and the radial grid is a poor approximation to the perfectly conducting plane assumed in the theoretical analysis.

7. INTERFACE EQUIPMENT AND OPERATIONAL TEST

Before an operational test of the antenna system could be undertaken a good bit of special hardware had to be designed for interfacing between the antenna-matching unit associated with the transmitter and the balloon-borne antenna. Interfacing involved making a high-current, high-voltage, corona-free connection between a fixed insulator on the antenna-matching unit and a bobbing feedpoint on the antenna, the latter being at the top of the inverted-T, which is a position nominally 20 feet above the earth's surface. A further requirement was that a sphere gap be included for lightning protection.

Circuit path for the interface extended about 10 feet horizontally outward from an insulator on top of the antenna-matching unit, at a level of about 5-1/2 feet, then down to a fixture across the top of a porcelain insulator 30-inches long and 11-inches in diameter, vertically up from there a distance of 20 feet, and finally across to the antenna feedpoint through a flexible cable. The high-voltage insulator was mounted on an aluminum frame that was solidly grounded at the point where the radials joined with the earth. A sphere gap for lightning protection was mounted between the grounded frame and the fixture at the top of the large insulator. Corona on the rigid part of the circuitry was avoided by using lengths of aluminum tubing of 1.7-inch diameter, with 6-inch diameter spheres at the ends, and large, smooth, machined joints for connecting sections of the tubing. Special corona-free, flexible joints were placed at the insulator on the antenna-matching unit, to avoid breakage there, and at the bottom of the long vertical pole. Insulating guys from the top and from the center held the pole upright. Connection from the top of the pole structure to the feedpoint of the antenna was by menas of a 30-foot long insulated cable of 4/0 size arranged in an inverted-U to allow the feedpoint to rise or fall.

Once all the hardware was designed, built, and assembled it was crated and subsequently shipped to Anniston, Alabama where an operational test was conducted. The antenna performed with good radiated signals, but the radial grid was not adequately bonded to the earth. As a result, currents flowing in the radial elements caused potential differences between those elements and the earth, with consequent sparking to ground at several locations. Burying the radials, or grounding them at more places along their length, should eliminate the problem and make the balloon-supported arrangement suitable for use in the event of an emergency. It should also be noted that tuning was accomplished with the existing antenna-matching unit, which means the geometrical arrangement originally specified did produce the desired electrical constants.

8. PHOTOGRAPHS OF HARDWARE ITEMS

Hardware items associated with the antenna are shown in photographs of Figs. 1 through 6. Construction of the tetrahedron and the inverted-T, can be seen in Fig. 1, the latter without the insulating tape that was used at the joints.

Fig. 2 shows the near spherical termination used at the outer end of the top loaders. Each half of the shell is a hemisphere, with a short cylindrical portion that fits over the ring that joins the two halves. The unit was placed around the tether at the outer end of the braid, the electrical connection to the braid being made within the sphere. Also, the polyethylene jacket was terminated inside the shell, which made a well-protected, flexible union at a critical position.

Features of the interface hardware needed for the Anniston test are indicated in Fig. 3. The portable base, the high-voltage insulator, the sphere gap, and the methods used for joining sections of aluminum tubing, and for terminating them, are evident. At the top of the insulator, at the left, can be seen the lower half of the flexible joint that mates with the long vertical pole, a junction identical with the one used at the antenna-matching unit, and shown at the far right.

Fig. 4 shows the ball half of the ball-and-socket joint used to provide flexibility at the lower end of the vertical pole. Not shown is a short length of cable, placed internally to provide a high-current connection between the two parts of the ball-and-socket joint.

For convenience in shipment the 20-foot long pole was made in two parts, and joined mechanically and electrically as indicated in Fig. 5. Also shown in this photograph is a corona-free donut to which nylon guys could be attached.

Fig. 6 shows how the top of the pole was terminated by a sphere with a donut located immediately below for anchoring the nylon guys that extend down from there. A large, smooth, corona-free clamp was used to connect the 30-foot length of insulated 4/0 copper cable to the pole, shown at the left, and a similar fixture was used to connect the cable to the upper end of the inverted-T, shown at the right.

9. CONCLUSIONS

The proposed design for a balloon-supported emergency back-up antenna for the Loran C/D navigation system was studied to determine whether corona formation on the top loaders could burn the KEVLAR cables to which the top loaders would be attached, and thereby threaten the safety of the system. Results of the extensive analysis indicated the proposed arrangement was unworkable because the corona loss at rated antenna voltage would far exceed the 30 kilowatts of power available from the transmitter. This work, along with a comparison study of the situation on the regularly used tower structure, pointed the way to a successful design that was implemented, and later given an operational test at the transmitting site at Anniston, Alabama. All hardware items needed to implement the design, and to interface the system for the operational test, were designed and manufactured.

Radiated signals in the Anniston operation were good, but the ground radials used in that exercise were not adequately joined with the earth, and this led to sparking at a number of locations. If the ground radials were either buried, or joined with the earth at more places along their length, the balloon-supported antenna should be useful as an emergency back-up.

Electrical constants of the antenna were well within the range of the antenna-matching unit, so there was no difficulty in tuning the transmitter when the balloon-borne antenna was used.

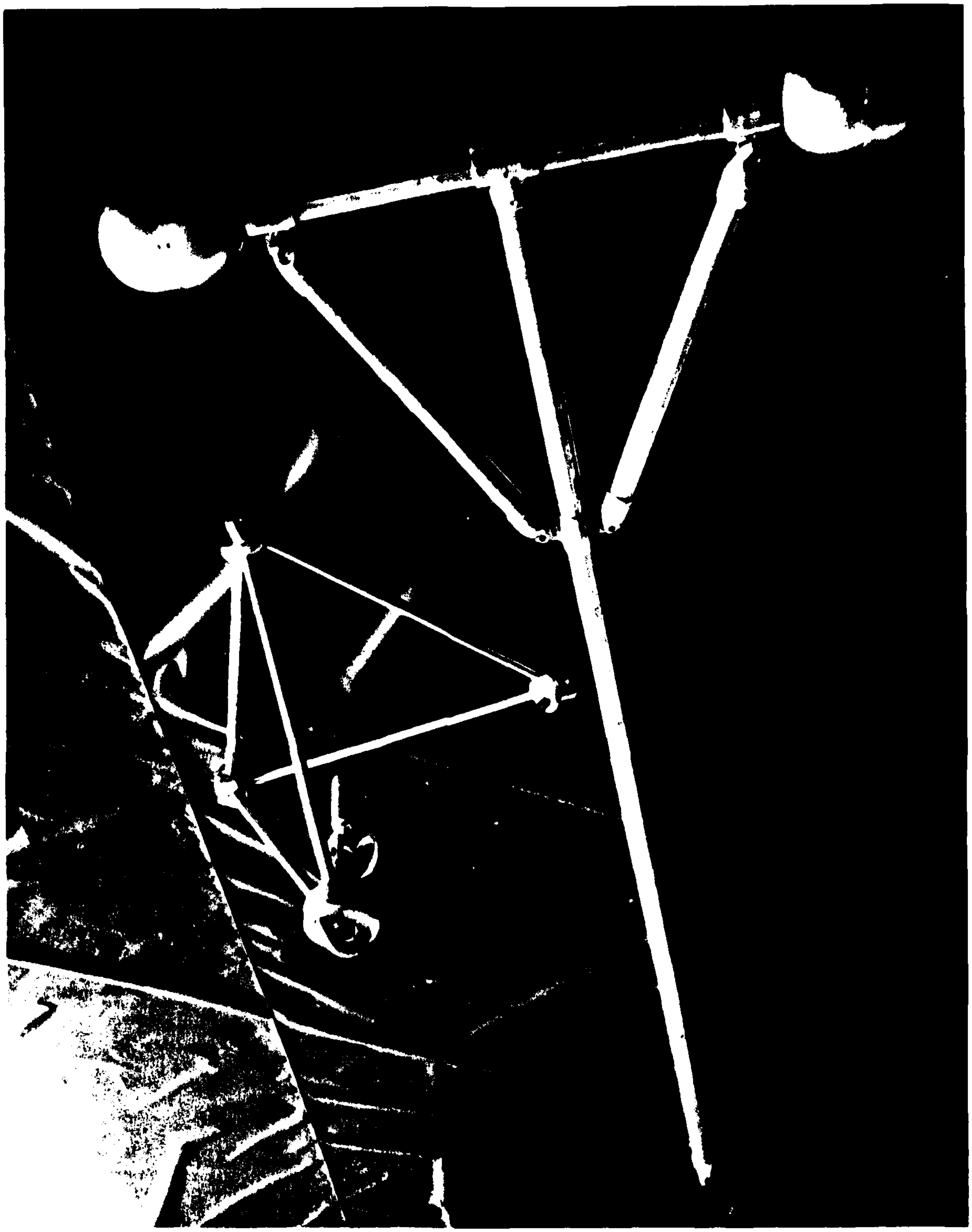

Figure 1. Tetrahedron and Inverted-T

Figure 2. Spherical Shells Used at Outer Ends of Top Loaders

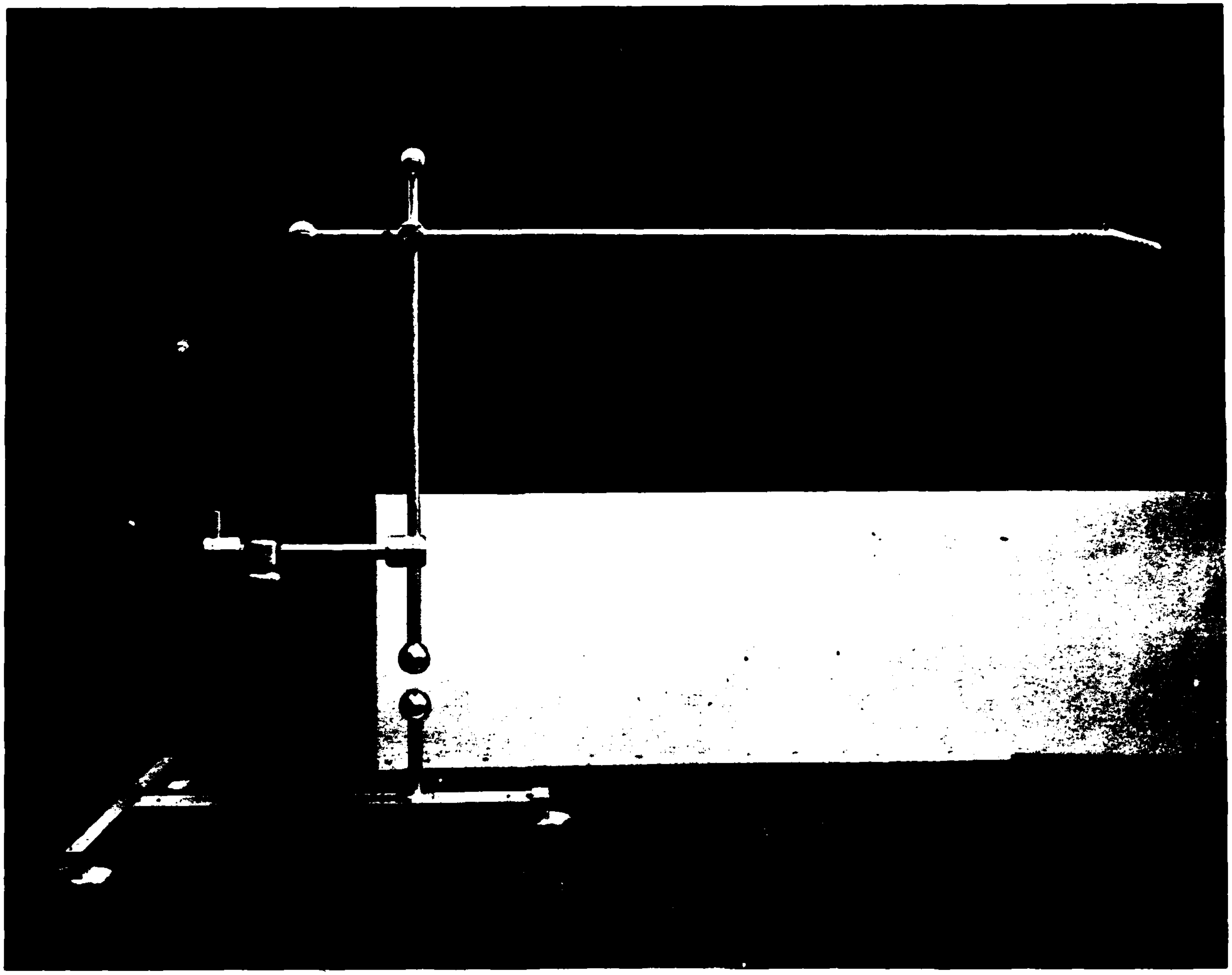

Figure 3. Portable Base Showing Sphere Gap and Design of Corona-Free Connections

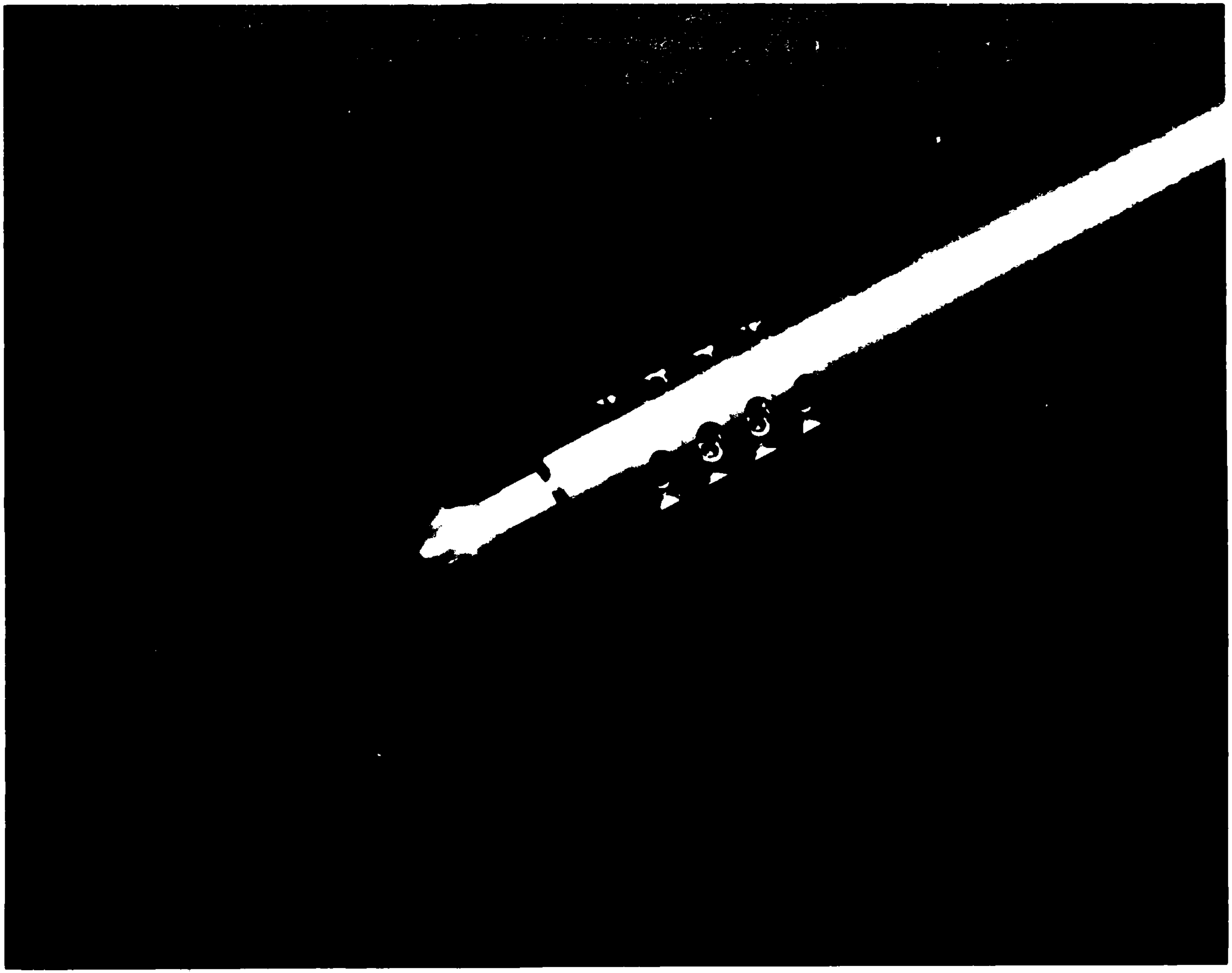

Figure 4. Ball Part of Ball-and-Socket Joint at Lower End of Vertical Pole

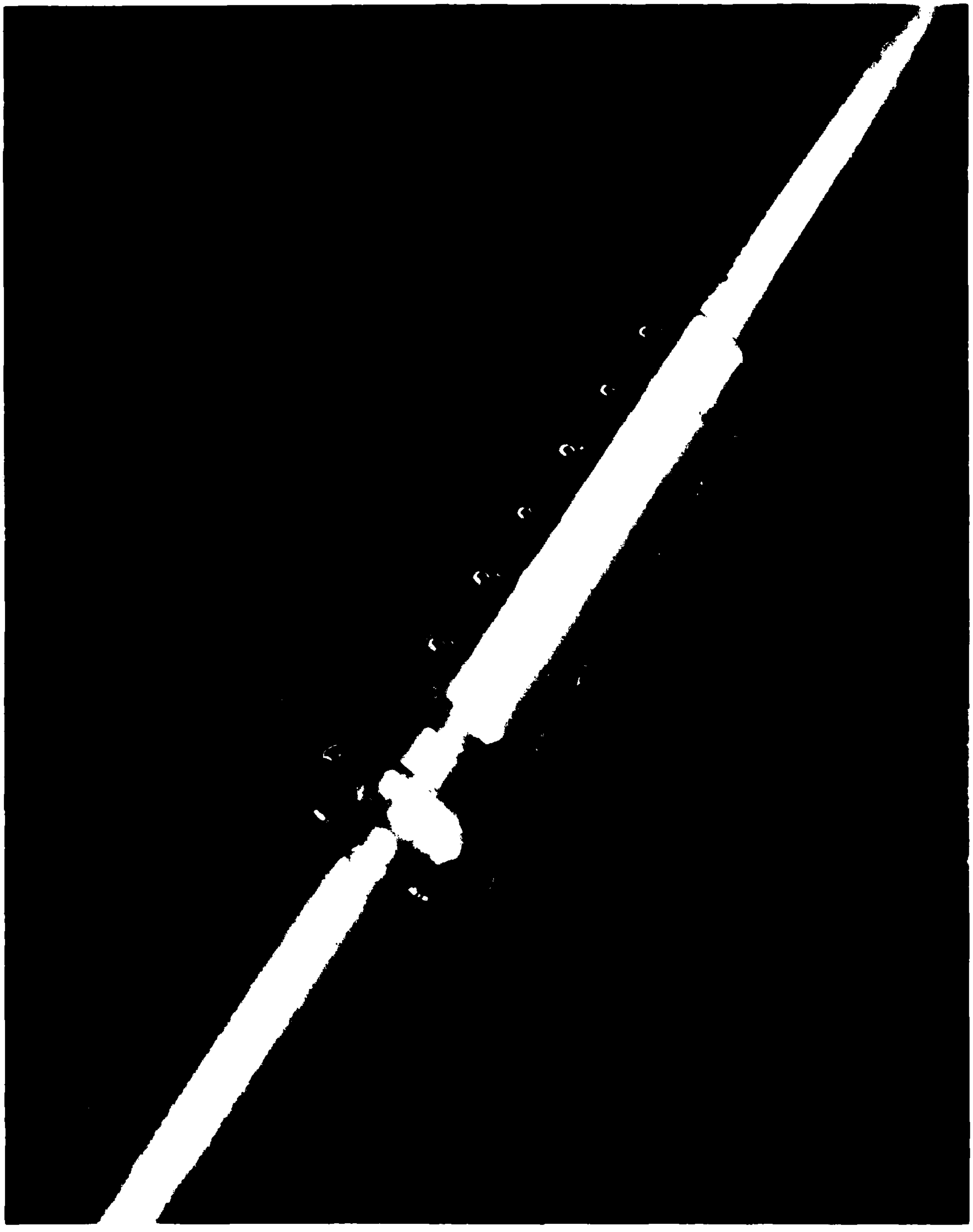

Figure 5. Long Vertical Pole Comprised Two 10-Foot Long Sections Joined as Indicated. Donut Served as Anchor for Nylon Guys

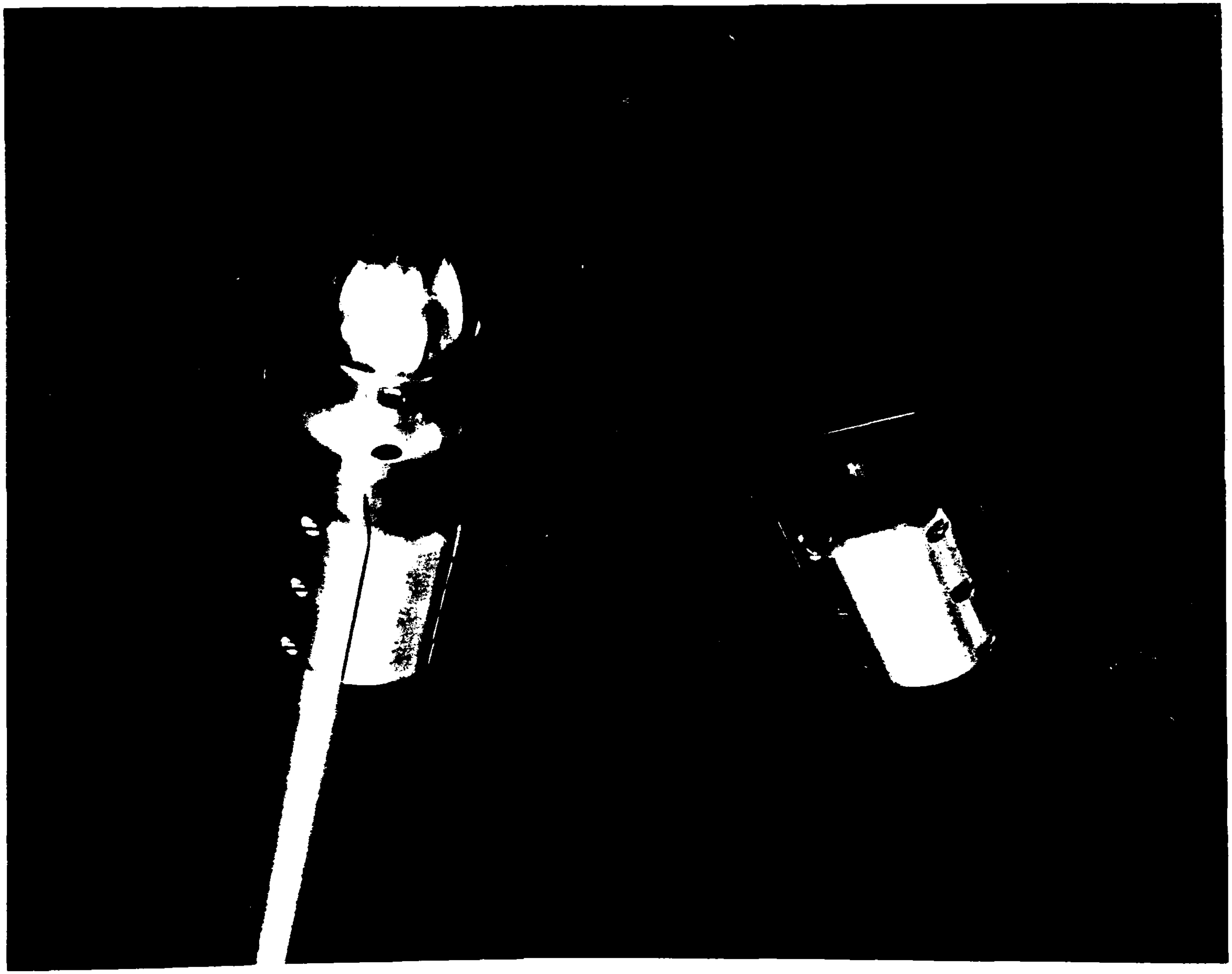

Figure 6. Sphere at Top of Vertical Pole, Donut for Anchoring Nylon Guys, and Fixture for Connecting Insulated 4/0 Copper Cable to Pole, Shown at the Left, with a Similar Fixture for Attachment to Top of the Inverted-T Shown at the Right